Journal of Arid Environments 165 (2019) 46–54

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Modelling the effects of climate factors on soil respiration across Mediterranean ecosystems

Sergio González-Ubierna[a], Roberto Lai[b,c,*]

[a] Departamento de Edafología, Facultad de Farmacia, Universidad Complutense de Madrid, Pza. Ramón y Cajal s/n (Ciudad Universitaria), 28040, Madrid, Spain
[b] Desertification Research Centre (NRD), University of Sassari, Viale Italia 39, 07100, Sassari, Italy
[c] Dipartimento di Agraria, University of Sassari, Viale Italia 39, 07100 Sassari, Italy

ARTICLE INFO

Keywords:
Agronomy
Irrigation
Mineralization
Soil carbon
Soil management

ABSTRACT

Soil CO_2 emissions are critical for climate change modelling. Although there is a consensus about the linear or exponential relations between soil respiration and climate factors, some works have shown this abstraction to be invalid under arid and semiarid conditions, especially those in the Mediterranean-type climate. In this work, the latest empirical models were tested on previously published data from three sites representing different agricultural areas under Mediterranean conditions and contrasting soil uses. Soil heterotrophic respiration, soil temperature and volumetric water content were monitored on average every two weeks in each site over at least one year. With the findings in the three sites in Spain and Italy, it can be concluded that soil temperature was the main driver of soil respiration, as in temperate sites. However, owing to the extreme variability in climate variables, soil moisture modulates the response of soil respiration to temperature changes, and is thus another key for modelling soil respiration in Mediterranean conditions. Irrigation practices with high water inputs also substantially modify the soil respiration pattern, causing it to become similar to temperate soils. Finally, the results indicate that annual extreme values may be especially relevant in the relationship between climate variables and soil CO_2 emissions.

1. Introduction

CO_2 emissions from soil are estimated to be ten times higher than those produced by burning fossil fuels (Oertel et al., 2016), accounting for 98 ± 12 Pg C annually (Bond-Lamberty and Thomson, 2010). Even though this contribution we have only a limited understanding of the variability across ecosystems and the controlling factors (Castillo-Monroy et al., 2011). The scientific community must shed light on a number of uncertainties such as the soil carbon (C) balance and the drivers and controls of soil carbon mineralization (Lai et al., 2017). Empirical relationships have been developed in single sites, with constant variables (such as vegetation, soil type, climate history) but usually are not compared with other sites (Trumbore et al., 2006), and the models are developed to seasonal variations, which are not always suitable over annual or longer timescales (Verburg et al., 2004; Scott-Denton et al., 2005). This is particularly significant in dry areas such as the Mediterranean region (Conant, 2009; Scholes et al., 2009), covering approximately 2.75 million km^2 of land (Rambal, 2001), and where Rs is considered to be one of the main C loss processes (Conant et al., 2000).

Soil CO_2 emissions or, following other authors such as Hanson et al. (2000), soil respiration (Rs) are today known to be directly related with climate factors such as soil temperature (Ts) and soil water content (soil moisture, Ms) (Davidson et al., 1998; Zhang et al., 2013). Although the linear indices in the relation between soil respiration and temperature have been widely used (Fang and Moncrieff, 2001), there is no agreement in the modelling to better explain how soil temperature affects soil respiration under high variable climates (Subke and Bahn, 2010). In these ecosystems highly susceptible to drought, Ts and Ms often interact to control Rs, with Rs responding to the most limiting factor (Correia et al., 2012; Almagro et al., 2009; Oyonarte et al., 2012). While Rs is generally constrained by low soil water content during summer months, abrupt and large soil CO_2 pulses have been observed after rewetting the dry soil (Jarvis et al., 2007; Inglima et al., 2009; Unger et al., 2012; Matteucci et al., 2015). This partially explains why attempting to model Rs using only temperature driven variables proved ineffective (Joffre et al., 2003; Migliavacca et al., 2011). Following these assumptions, the Q_{10} index is not useful in arid and semiarid environments (Davidson and Janssens, 2006; Matteucci et al., 2015, among others), and a new approach must be designed for these soils. One main issue in modelling

* Corresponding author. Desertification Research Centre (NRD), University of Sassari, Viale Italia 39, 07100 Sassari, Italy.
E-mail address: rlai@uniss.it (R. Lai).

https://doi.org/10.1016/j.jaridenv.2019.02.008
Received 29 April 2018; Received in revised form 3 February 2019; Accepted 13 February 2019
Available online 14 March 2019
0140-1963/ © 2019 Published by Elsevier Ltd.

soil respiration through soil temperature variation is that the role of soil moisture is reduced to a limiter in linear temperature dependence models with a fixed Q_{10} (Balogh et al., 2011; Suseela et al., 2014).

Some authors have explored other approaches, Mancinelli et al. (2010) showed a polynomial Rs response to Ts variation, although irrigation restored 90% of the Ms lost through evapotranspiration during the aridity period. This finding was not consistent with the findings reported by Davidson et al. (1998) for a forestry system, who found an exponential relationship between Ts and Rs. While some authors have demonstrated the critical effect of Ts and Ms interactions (Craine and Gelderman, 2011), calling into question the use of linear regressions and constant Q_{10} (Xu and Qi, 2001). This is especially important in the Mediterranean climate where, following the studies of Almagro et al. (2009), de Dato et al. (2010) and Oyonarte et al. (2012), Ts and Ms vary widely and concurrently. Following these conclusions, some studies have analysed the influence of both soil temperature and moisture (Martin and Bolstad, 2009) on the soil respiration process, showing that the relationship between soil respiration and soil temperature varies according to moisture thresholds (Lellei-Kovács et al., 2011).

In a past research (Gonzalez-Ubierna et al., 2012) we tested the most used models to represent the relationships between Rs and climate factors (Lellei-Kovács et al., 2011), developing a modification of Martin and Bolstad model (Martin and Bolstad, 2009) to include both variables in the same model. For the specific conditions of a fallow plots in the center of Iberian Penninsula this model demonstrated to be the most accurate.

Due to the seen difficulties in the duplicability of the models in high variability climates, the main aim of this work is to test the approaches in modelling the influence of climate variables on soil respiration, applied in the Gonzalez-Ubierna et al. (2012) and in others works, in different sites of the Mediterranean basin, with different soil use and climatic conditions. Moreover, aims of this work is to evaluate the reliability of the results to make the applicability of the developed model stronger, and to show the evolution in time of the soil heterotrophic respiration, and evaluating the role of climate variables on it.

2. Material and methods

2.1. Study areas

Data were compared on heterotrophic soil respiration from four different studies, all in a Mediterranean climate type (Fig. 1): the first in Berchidda, in northern Sardinia (Italy), the second in Arborea, in central Sardinia (Italy), and the last two in the same area in the Madrid region, in the central Iberian Peninsula (Spain). The Spanish studies can be seen in González-Ubierna et al. (2013) and González-Ubierna et al. (2014), and the Italian studies were published in Lai (2011), Lai et al. (2012) and Lai et al. (2017). The data from Madrid have been aggregated into one group to represent the same area. Three different sites for analysis have therefore been considered in this work: Berchidda, Arborea and Madrid.

The data for Berchidda (Lai, 2011) was collected in the Long-Term Observatory of Berchidda-Monti, Sardinia, Italy (40°47′0″N 09°10′0″E, 320 m amsl), 34 km from the sea. The site is described in Lagomarsino et al. (2011) and Seddaiu et al. (2013). According to Rivas-Martínez et al. (2011), the climate is Mediterranean pluviseasonal oceanic, low mesomediterranean (Bagella et al., 2013). The mean annual rainfall is 630 mm, 70% of which occurs from October to March (Seddaiu et al., 2013). The mean annual temperature is 14.2 °C (Cappai et al., 2017). The soil is formed from granitic rock, a parent material that is widespread in Sardinia (Carmignani et al., 2008), and is classified as Haplic Endoleptic Cambisol, Dystric (WRB, 2006) with a sandy loam texture (Francaviglia et al., 2012). In this area the most frequent land uses are wooded grasslands and vineyards (Lai et al., 2014).

The data for Arborea (Lai et al., 2012, 2017) was collected on a farm located in the dairy district of Arborea, Italy (39°47′ N 8°33’ E, 3 m amsl). The area is characterized by a typical Mediterranean climate, with long, hot, dry summers (June to September) and short, mild, rainy winters with a mean annual temperature of 16.7 °C and precipitation of 568 mm (1959–2012). The soils are classified as Haplic Lixisols, Arenic (WRB, 2006). Following Rivas-Martínez et al. (2011), the climate is Mediterranean pluviseasonal oceanic, upper thermomediterranean low dry (Lai et al., 2012). The cropping system is based on the double-crop rotation of silage maize (Zea mays L.) from June to September and an autumn-spring hay crop from October to May. Slurry or manure is applied prior to sowing each crop and combined with mineral fertilization. Mineral fertilizers are applied at the end of the winter during the autumn-spring hay crop to compensate for insufficient soil mineral N availability, while maize is fertilized in summer at sowing. Irrigation is provided from late spring to September to maintain the soil water content at a field capacity of 600 mm per year. More agronomical information on the Arborea site is reported in Demurtas et al. (2016).

In all of the Itlian studies heterotrophic soil respiration was determined by the trenching method following Hanson et al. (2000).

The Spanish site was an experimental station located in the city of Arganda del Rey, in the southeast of the Madrid Region, Madrid (UTM X: 457673.84, UTM Y: 4462824.553). The site has a typical Mediterranean pluviseasonal oceanic dry meso-Mediterranean bioclimate (Rivas-Martínez et al., 2011). Geomorphologically, the area lies on the former alluvial terrace on the left bank of the Jarama river basin on quaternary calcareous sediments with high carbonate contents. These alluvial sediments have caused an ancient calcareous fluvisol,

Fig. 1. Localization of the experimental sites of the studies compared.

which has anthrosol (WRB, 2006) characteristics today, due to its historical agricultural land use. Morphologically, an Ap horizon (0–40 cm) can be distinguished with properties similar to an anthragric horizon, low surface stoniness, high permeability and a subsurface with the typical characteristics of agricultural land, showing subsurface compaction due to the intensive use of farm machinery (Casermeiro et al., 2007). The land use of the experimental site during the monitoring years was fallow, from a historical non-irrigated crop.

2.2. Experimental plot design and sampling

Soil heterotrophic respiration (Rs) was measured *in situ* in all sites. In Madrid the data was measured with a model Li-COR 8100 infrared gas analyzer with an open chamber with a diameter of 20 cm (Savage and Davidson, 2003); while a portable closed-chamber soil respiration system (EGM-4 with SRC-1, PP-System, UK) was used in Berchidda and Arborea. In all sites, all measurement lengths were 120 s and performed between 8:00 and 13:00 (standard time). Each measuring point was artificially maintained without vegetation. The measurements were performed on soil areas with a diameter of at least 10 cm and at a field point that was representative of the main spatial variation of the sites (e.g. soil use and absence or presence of trees on the Berchidda site, fertilization management in Arborea and along one alluvial terrace in Madrid). Rs data were measured on average twice a month over a period of at least one year in Italy and in the studies by González-Ubierna et al. (2014). In the remaining case (González-Ubierna et al., 2013), soil CO_2 emissions were measured twice a month for two years. Ts and Ms were measured at the same time as Rs, either with a portable thermometer and a DIVINER 2000 (Sentek, AU) at −10 cm and 0–20 cm respectively in Berchidda and Arborea, or by monitoring with a Jet Fill 2725 tensiometer equipped with a thermometer inserted in the soil (Soil Moisture Equipment Corp.) in the Spanish case, at a depth of 5 cm from the soil surface. Following Cardenas-Lailhacar and Duke (2010), tensiometers are considered a standard and well-known method for soil water estimation in soils. Data in Berchidda were collected under or outside the tree canopy in the grasslands, and data from the vineyards were pooled together considering three different replication plots (under the canopy, outside the canopy and in the vineyard). In Arborea, the data from the same fertilization treatment were pooled together to give four different replications. Three separated plots (i.e. replications) were monitored for Madrid, pooling together the three measuring points in each one. Statistical analyses therefore consisted of n = 3 for Berchidda, n = 4 for Arborea and n = 3 for Madrid.

2.3. Data analysis

The relationship between soil climate conditions and Rs was analysed using five different approaches (Table 3) to test the simple effect of Ts and Ms on Rs, assuming micro-temporal variation negligible. Gaussian temperature function including interactive soil moisture effect was used following Lellei-Kovács et al. (2011). The linear relation, the exponential model and its modification by Zhang et al. (2010), and Lloyd and Taylor's approach (Lloyd and Taylor, 1994) were also tested. All these models assume a linear relationship between soil climate variables and Rs, involving a constant effect of Ts or Ms on Rs. Finally, the Gaussian model was added (the best approach in Lellei-Kovács (2011) and González-Ubierna et al. (2014), which assumes an optimum value of climate variables (Ts or Ms) resulting in a maximum Rs, and thus a non-linear relationship.

Five models were also tested in order to represent the effect of both climate parameters on Rs: the modified Martin and Bolstad model, Vargas and Allen's (2008) approach, two models from the study by Zhang et al. (2010), and the approach described in Xiao et al. (2009) (Table 3).

Finally, the influence of the interaction of soil and climatic variables on Rs was further explored by analysing first the relation between Rs and Ts in three Ms thresholds: when Ms is below the optimum (detected by Gaussian model runs), when Ms is above the optimum, and when Ms is around the optimum (in every case ± 1% Ms); and then the relationship between Rs and Ms in the same three thresholds, but for Ts values in relation to the optimum Ts (± 1 °C Ts). It should be noted here that statistical correlation analysis assumes a linear relation, and cannot therefore be used in an annual approach in Mediterranean sites. However, it was used in the study of these thresholds, since when working with partial rather than annual data, linear approaches are more effective (González-Ubierna et al., 2014). Lellei-Kovács et al. (2011) showed that the optimum in Ts or Ms for soil respiration only can be detected in field measurements performed in sufficiently broad

Table 1
Main climatic, soil characteristics (0–20 cm) and uses of the sites (mean data from three independent samples).

	Unit	Madrid	Berchidda	Arborea
Texture (g kg^{-1})	Silt	412.8	119.9	14.0
	Sand	313.8	800.6	970.0
	Clay	273.4	79.5	16.0
	Class	Coarse clay	Sandy loam	Sandy
Bulk Density	g cm^{-3}	1.5	1.3	1.5
Organic Carbon	g kg^{-1}	13.08	18.00	13.60
Available water-holding capacity	m^3 m^{-3}	0.20	0.15	0.16
C/N ratio		9.5	12	10
pH	–	8.30	5.70	6.30
Land Use	–	Fallow	Vineyard and grassland	Cropland
Annual Mean T	°C	19.0	14.2	16.7
Rainfall	mm	430	630	572

Table 2
ANOVA results.

		df	*F*	*p*
Annual Data				
CO_2	Between groups	2	13.41	.00
	Within groups	1243		
Ts	Between groups	2	4.11	.02
	Within groups	1246		
Ms	Between groups	2	17.96	.00
	Within groups	1251		
Summer Data				
CO_2	Between groups	2	13.60	.00
	Within groups	405		
Ts	Between groups	2	1.05	.35
	Within groups	406		
Ms	Between groups	2	1.91	.15
	Within groups	405		
Autumn Data				
CO_2	Between groups	2	12.31	.00
	Within groups	310		
Ts	Between groups	2	12.31	.00
	Within groups	311		
Ms	Between groups	2	45.88	.00
	Within groups	311		
Winter Data				
CO_2	Between groups	2	3.42	.03
	Within groups	287		
Ts	Between groups	2	16.85	.00
	Within groups	288		
Ms	Between groups	2	19.39	.00
	Within groups	291		
Spring Data				
CO_2	Between groups	2	7.11	.00
	Within groups	232		
Ts	Between groups	2	2.45	.09
	Within groups	232		
Ms	Between groups	2	.60	.55
	Within groups	235		

Ts = Soil temperature; Ms = Soil moisture.

Table 3
Parameters (b1, b2 and b3) and determination coefficients (r^2) of soil temperature (Ts) and soil moisture (Ms) dependence models.

	Temperature					Moisture				
	b1	b2 (Ts)	b3 (Ts^2)	r^2	AIC	b1	b2 (Ms)	b3 (Ms^2)	r^2	AIC
MADRID										
Lineal	1.427	0.098	–	0.183	*−1621.00*	3.554	−0.048	–	0.057	*−1420.00*
Lloyd and Taylor	0.587	0.193	−0.005	0.306	*−1923.00*	1.215	0.155	−0.005	0.245	*−1755.00*
Exponential	1.255	0.043	–	0.281	*−1796.00*	3.509	−0.026	–	0.132	*−1613.00*
Zhang	−0.873	0.479	−0.012	0.303	*−1762.00*	0.946	0.365	−0.012	0.228	*−1585.00*
Gauss	−0.532	0.193	−0.005	0.306	*−1923.00*	0.195	0.155	−0.005	0.245	*−1755.00*
ARBOREA										
Lineal	−1.059	0.206	–	0.364	*−360.80*	1.985	0.009	–	0.001	*−258.50*
Lloyd and Taylor	2.736	−0.160	0.008	0.492	*−398.60*	0.196	0.245	−0.006	0.056	*−284.10*
Exponential	0.437	0.090	–	0.561	*−398.00*	1.868	−0.003	–	0.001	*−279.00*
Zhang	2.927	−0.362	0.018	0.425	*−360.70*	−1.748	0.406	−0.010	0.049	*−264.10*
Gauss	1.006	−0.160	0.008	0.492	*−398.60*	−1.631	0.245	−0.006	0.056	*−284.10*
BERCHIDDA										
Lineal	1.839	0.033	–	0.034	*−100.40*	2.454	−0.009	–	0.001	*−97.55*
Lloyd and Taylor	0.191	0.300	−0.008	0.369	*−115.90*	0.264	0.364	−0.013	0.226	*−106.80*
Exponential	1.183	0.028	–	0.117	*−98.09*	2.453	−0.022	–	0.023	*−94.76*
Zhang	−1.718	0.475	−0.011	0.309	*−110.60*	−1.332	0.628	−0.023	0.206	*−104.00*
Gauss	−1.656	0.300	−0.008	0.369	*−115.90*	−1.330	0.364	−0.013	0.226	*−106.80*

All models have been tested for a confidence interval of 95% ($P < 0.05$).

ranges.

The statistical treatment of the results was done with SPSS v.17 in the Microsoft Windows operating system. Analysis of variance (ANOVA) was done using the F distribution method –Fisher-Snedecor– with a confidence level of 95% ($p < 0.05$), while correlation analysis was a non-parametric correlation (Spearman's Rho). An Akaike Information Criterion (AIC) was done to select the best model in each analysis. This analysis was carried out using SAS analytic software.

3. Results

3.1. Dynamics of Ts, Ms and soil respiration

Rs followed a similar pattern in the three sites, with clear seasonality even in irrigated soils in Arborea. Rs was observed to peak in spring (around May in Madrid and in June in Arborea) and enter a minimum in autumn and winter (Fig. 2).

Rs rates ranged from 0.22 to 6.99 (± 0.03) μmol CO_2 m^{-2} s^{-1} in the Berchidda site, 0.46 to 11.62 (± 0.05) in Arborea, and 0.20 to 13.14 (± 0.01) in Madrid. ANOVA analysis (Table 2) showed that Rs in the Italian sites was significantly lower than in Madrid ($p < 0,01$). These statistical results varying along the year: no differences were found in winter and autumn ($p < 0,05$), while in spring Berchidda showed the highest data and Arborea did it in summer ($p < 0,01$ for both analysis).

The climate parameters follow the similar trends in Madrid and Arborea (without any statistical difference), with significant higher Ms and lower Ts values than Berchidda ($p < 0,05$). The particularly wet year of measurement could explain these results even when Madrid has a dryer climate (430 mm in Madrid and 600 mm in Berchidda in a 30-year data range). The higher continentality of Madrid produced the minimum values of Ms and Ts, and the highest range of Ms. Meanwhile, Arborea showed the highest range of Ts and the highest values of both variables (Fig. 3). There seems to be no clear relation between the evolution of climate variables and the pattern in Rs. Only in summer was a parallel pattern between Rs and climate data.

3.2. Relations of Ts and Ms on Rs

It was observed that the Gaussian and Lloyd and Taylor approaches most effectively represented the influence of Ts on Rs in Madrid and Berchidda, based on AIC results; however, although this model produced good results in Arborea, the exponential approach showed similar AIC results and the best coefficient of determination (Table 3). The application of the model showed a positive effect of Ts in Rs in all cases, with the highest influence in Arborea, and the lowest in Berchidda. The application of the Gaussian model also revealed a maximum Rs when the Ts was 19 °C in both Madrid and Berchidda. However, the model gave no maximum for Rs in Arborea, thus reinforcing the exponential approach. It is particularly worth noting the results of the

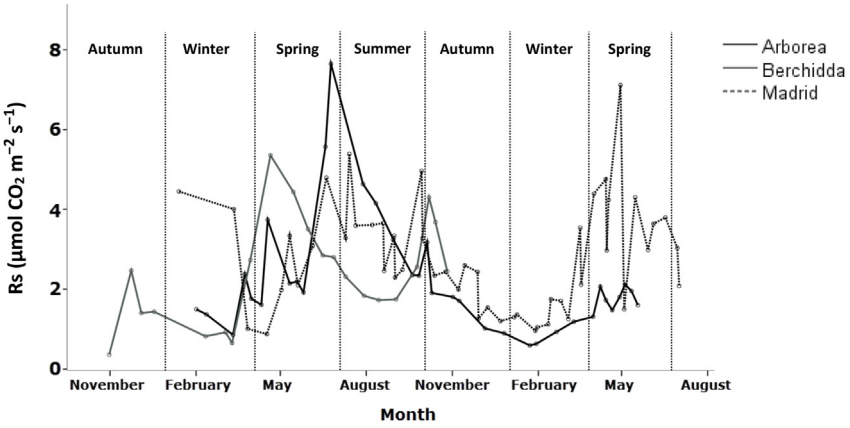

Fig. 2. Soil respiration (Rs) evolution in the three studies compared.

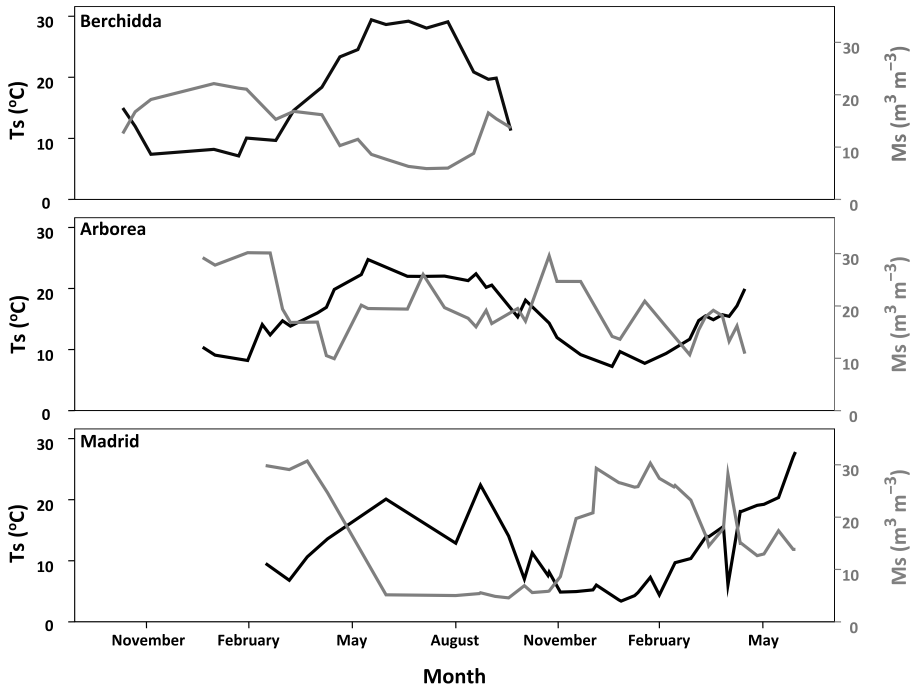

Fig. 3. Soil temperature (Ts) and moisture (Ms) evolutions in the three studies compared.

linear model, which was not useful for representing the relations between Ts and Rs in Madrid and Berchidda, but obtained an excellent fit in Arborea (albeit not the best).

As in the case of Ts, the Gaussian and Lloyd and Taylor approaches gave the best results for representing the influence of Ms on Rs (Table 3). With the exception of the Zhang approach, the rest of models tested did not produce a good fit. The application of the models showed a negative correlation between Ms and Rs in Madrid and Berchidda, while there was no relation in the Arborea site. Deepen in the analysis, the Gaussian approach showed that Ms was positively related with Rs when Ms was less than 0.16 $m^3 m^{-3}$, and negatively related above this value in Madrid. In Arborea the Ms threshold was 0.20 $m^3 m^{-3}$, and 0.14 $m^3 m^{-3}$ in Berchidda. In general, soil water content had a greater effect in Berchidda CO2 emissions; however, at Ms levels below the wilting point (0.04 m^3 m-3 in Madrid (Jiménez-Hernández et al., 2009) and 0.02 m^3 m-3 in Berchidda) it had a greater effect on Spanish soils. Meanwhile, Arborea showed a low effect of Ms on Rs.

3.3. Interaction between Ts and Ms in the influence on Rs

The results of the Ts threshold influence on Ms-Rs relations (Table 4) showed a negative relation between them when Ts was below the optimum in Berchidda and Madrid (< 19 °C). When Ts was near the optimum (19 °C), Ms was related with Rs only in Madrid, with a positive sign. In the last threshold, (Ts > 19 °C), the relation between Ms and Rs was positive in Madrid and negative in Berchidda. Finally, Ms was not significantly related with Rs in Arborea in any threshold.

The results showed a positive relation between Ts and Rs for the Ms thresholds in all cases for the Arborea site. In Madrid, when the Ms was near the optimum this relation was negative, while in the other two situations this relation was positive. In the Berchidda site the relation was positive when Ms was below the optimum, and negative when it was above.

In the analysis of the models with the combination of the two climate variables to explain Rs evolution (Table 5), the modified Martin and Bolstad model obtained the best results (AIC and R2) in Madrid and Berchidda, while Zang II worked better in Arborea (AIC).

The application of the first model revealed a higher basal Rs in Berchidda, and a higher impact of climate factors in Madrid. Ts was the main factor influencing Rs in all three sites. This model also highlighted the interactions described above –with a threshold of 12 °C in Berchidda, separating the positive and negative effect of Ms on Rs. The Ts threshold for the change in the sense (negative to positive) of the relation Ms-Rs was not showed by the model in Madrid, where was defined by the soil water content (0.16 m^3 m-3).

4. Discussion

4.1. Comparisons of the dynamics of Ts, Ms and Rs with previous results of Mediterranean studies

The Rs pattern in the three sites highlighted the critical importance of Ts, with a marked minimum in autumn and winter. However, the peaks in CO_2 emissions occurred in spring, due to the increase in Ms

Table 4
Correlation analysis results between soil temperature (Ts) and soil respiration at different thresholds of soil moisture (Ms), and between soil moisture and soil respiration at different soil temperature thresholds. Opti reflects the range of soil temperature (°C) or soil moisture ($m^3 m^{-3}$) values, detected as optimum for soil CO_2 emissions.

	Ms	Ts < Opti	Ts = Opti	Ts > Opti	Ts	Ms < Opti	Ms = Opti	Ms > Opti
Berchidda	−0.143	−0.560**	0.086	0.872**	0.265*	−0.438**	0.343	0.703**
Arborea	−0.033	−0.083	0.197	0.355	0.740**	0.558**	0.744**	0.681**
Madrid	−0.396**	−0.415**	0.521**	−0.690**	0.640**	0.490**	−0.439**	0.452**

** Reflects statistical significance for a confidence interval of 99% (P < 0.01).

Table 5
Parameters (b1-b7) and determination coefficients (r^2) of models tested for synergic effect of soil temperature (Ts) and soil moisture (Ms).

	b1	b2 (Ts)	b3 (Ts^2)	b4 (Ms)	b5 (Ms^2)	b6 (TsMs)	r^2	AIC
MADRID								
Martin & Bolstad	−0.351	0.152	−0.004	0.093	−0.003	−0.001	0.527	*−2055.00*
Zhang	2.893	−0.016	–	−0.104	–	0.010	0.259	*−1687.00*
Zhang II	0.480	0.614	–	0.086	–	–	0.248	*−1876.00*
Xiao	1.560	0.038	–	0.024	–	–	0.173	*−1801.00*
Vargas and Allen	1.094	0.018	–	0.123	−0.004	–	0.277	*−1888.00*
ARBOREA								
Martin & Bolstad	0.795	−0.009	0.001	−0.032	0.000	0.003	0.581	*−407.30*
Zhang	1.174	−0.034	–	−0.123	–	0.013	0.439	*−374.90*
Zhang II	0.001	1.937	–	0.757	–	–	0.463	*−413.20*
Xiao	0.037	0.119	–	0.694	–	–	0.494	*−405.30*
Vargas and Allen	0.100	0.119	–	0.072	−0.001	–	0.495	*−403.40*
BERCHIDDA								
Martin & Bolstad	1.276	−0.007	−0.001	−0.069	5.06*10-5	0.006	0.527	*−130.40*
Zhang	4.236	−0.173	–	−0.263	–	0.023	0.465	*−123.30*
Zhang II	0.004	1.207	–	1.152	–	–	0.345	*−113.50*
Xiao	0.088	0.052	–	0.924	–	–	0.166	*−100.20*
Vargas and Allen	0.047	0.041	–	0.472	−0.015	–	0.407	*−112.90*

All models have been tested for a confidence interval of 95% ($P < 0.05$).

and the effect of rewetting associated to rainfall events. Low Rs values in summer, detected by some authors as the moment of minimum values (Almagro et al., 2009), was observed only in Berchidda, although this decrease was not as great as in the cold period. At this point a clear pattern was observed in Arborea, since without the modulating influence of Ms on the effect of Ts on Rs (Lellei-Kovács et al., 2011) there were not significant peaks from summer to winter. However, Berchidda and Madrid showed a peak in early autumn or late summer due to moderate Ts and the start of the rainfall (increased Ms). Gaumont-Guay et al. (2006) pointed to a strong seasonal hysteresis as an explanation for this effect. Finally, the unusually wet year in Madrid explained the absence of a higher peak in spring, due to the moderate effect of rewetting, but not in the second year, where a spring peak could be observed.

The highest Rs rates were found in Madrid, and could be associated with three factors:

1. The convergence of mean values of Ts and Ms in Madrid, which produces optimum climate conditions for microbial activities, as in the study by Mancinelli et al. (2010). High water contents can impede the diffusion of CO_2 through the soil profile (Skopp et al., 1990), while low soil water content and/or low soil temperatures can reduce soil microbial activity (Davidson et al., 1998; Curiel Yuste et al., 2003). Finally, high Ts have a negative effect on Ms, leading to low water content as mentioned previously.

2. Differences in pH values (acidic soils in Italy and basic in Madrid, as seen in Table 1), since many authors have indicated the relevance of acidity in soil C decomposition rates and its influence on the relationship between Rs and soil climate factors. (von Lützow and Kögel-Knabner, 2009).

3. Finally, although there are no data available to confirm this, some authors have shown that fallow land use causes lower soil protection against rainfall, and a disruption in soil aggregates has been related to higher CO_2 emissions due to the mobilization of carbon forms inside the aggregate (Navarro-García et al., 2012). The substitution of fallow periods by any crop has been associated with SOC stabilization (Álvaro-Fuentes et al., 2009) and is considered a soil C sequestration strategy (Paustian et al., 2016).

No statistical differences were found between sites in the cold seasons (autumn and winter) due to this critical effect of environmental conditions. Rs was highest in summer due to the optimum soil climate conditions, while differences between sites were driven by Ms. Finally, in spring, non-irrigated soils (Berchidda and Madrid) showed higher CO_2 emissions than Arborea, in line with the absence of water limitations in this season, and the respiration pulses associated to rainfalls (Almagro et al., 2009). The priming effect of the rewetting processes in rainfall (Kuzyakov et al., 2000) is more intense in dry than in irrigated soils.

4.2. Effects of the climate factors on Rs

4.2.1. Effect of Ts on Rh

As observed by many authors (Tuomi et al., 2008; González-Ubierna et al., 2013; and Lellei-Kovács et al., 2011), and as expected, the Gaussian approach was the best model for representing the influence of Ts on Rs under the Mediterranean-type climate. Our results confirm these findings in a comparison between three different Mediterranean case studies. Nevertheless, as in Potner et al. (2010), Lloyd and Taylor approach have obtained similar AIC results. These authors, however, indicate that Lloyd-Taylor functions would have to be complemented by an additional curve and parameters describing the decline in respiration rates at high temperatures. In addition, Li et al. (2008) showed that Lloyd and Taylor functions relating CO2 efflux *vs* Ts could be used to predict the Rs whenever Ws was above a threshold of approximately 1/3 of WHC. Other authors, as Richardson et al., 2006, avoid the use of Lloyd and Taylor model. The inefficiency and inconvenience of using linear indices to represent Ts dependence on Rs under these conditions (Xu and Qi, 2001) was also demonstrated, as linear and exponential models obtained the worst fit. The exponential approach gave the best fit in the Arborea site. This was related to land use, since irrigation practices with high water inputs influence this relation and render it more similar to temperate soils. The reduction in CO_2 emissions at high Ts was related to the negative influence of Ms. Rs significantly decreases with water stress, associated to an inhibition of soil microbiological carbon decomposition (Jarvis et al., 2007). When water is not limiting, Rs generally increases with Ts (Inglima et al., 2009), since Ts is not a restricting factor for heterotrophic populations in irrigated crops grown under Mediterranean conditions (Onoyarte et al., 2012). The elimination of the water deficit therefore removes the distinctive characteristic of the Mediterranean climate (soil water deficit).

The positive relation between Ts and Rs has also been widely demonstrated in all climate types (Webster et al. (2009) described some examples), although the intensity of this dependence varies with soil and climate conditions. In our case, the Arborea site showed the highest dependence due to the microbiological effect of soil fertilization (Lopez-Lopez et al., 2006), and the absence of soil water limitation (Lai et al., 2017). The nitrogen availability for soil microorganisms controls the dynamics of the organic matter transformation (Hamer and Marschner, 2005), and a high sensitivity has been reported to temperature in SOC

microbial decomposition after the addition of labile organic matter (Gershenson et al., 2009).

This is also the reason that no optimum Ts was observed in these soils. Berchidda and Madrid showed a similar pattern, with an optimum Rs when the Ts was around 19 °C. This result was similar to previous studies such as González-Ubierna et al. (2014) and Thierron and Laudelout (1996), who found maximum Rs at 20 °C. Without the Gaussian approach, Conant et al. (2004) describe Rs as increasing with Ts up to 15 °C, after which this sensitivity decreases; while the model of Rey et al. (2002) fixed this point at 20 °C. The only difference found between Madrid and Berchidda is also due to changes in Rs Ts sensitivity. A lower Rs dependence was found in Berchidda than in Madrid when the Ts was above the optimum (19 °C); while at low Ts (below the optimum) the results showed a higher influence of Ts than in Madrid. This could be explained by the higher Ms in Madrid, since the decrease in Rs Ts sensitivity at high Ts accelerates with soil dryness (Conant et al., 2004). The differences in soil texture and pH could also account for these differences: a higher bulk density hinders aeration, microbial activity (CO_2 production), and CO_2 fluxes through soils when they have a high water content in their pores (see bulk densities in Table 1). In soils with an acidic pH, as pointed out by Leifeld et al. (2008), the effect of warming on decomposition is reduced due to the combined effects of enzyme/microbial activities (Walse et al., 1998). Nevertheless, further investigation is needed to study the effect of different types of soil water inputs (including irrigation) on Ts sensitivity.

4.2.2. Effect of Ms on Rs

As in the case of Ts, the best results for the models tested to represent the relations between Ms and Rs under Mediterranean conditions were achieved with the Gaussian approach. This was previously observed by González-Ubierna et al. (2015), and indicates that the Mediterranean climate does not influence Rs following the accepted approaches for other climate types. Moyano et al. (2012) showed that the general relationship between Ms and microbial activity can be described by a curve with minimums at both moisture extremes and a maximum at a moisture content where the balance of water and oxygen availability is optimal. However, the result was not as good as for the first variable in Arborea, and the relation should possibly be modelled by another type of approach (e.g., Pulina et al., 2017). Our results, therefore, according to previous literature, supported the idea that irrigated soils behave differently under Mediterranean conditions compared to soils with water limitations. The absence of extreme values of Ms, the lowest in this case, could explain this phenomenon by limiting the range of Ms measured and modelled. The optimum soil water content values for Rs in Berchidda and Madrid were near those reported by Onoyarte et al. (2012) (0.15–0.20 $m^3\ m^{-3}$). Therefore our results corroborated what already observed under Mediterranean climate and semi natural conditions.

As in other studies, the relations between Ms on Rs were negative under Mediterranean conditions (Almagro et al., 2009). Once again the Arborea site was the exception, with a positive but very low effect of Ms on Rs. According to Luo and Zhou (2006), Rs is maximum when Ms is near field capacity; the macropores are filled with air and the micropores are waterlogged, facilitating the diffusion of both O_2 and soluble substrates. When soil is anthropologically forced to these conditions (irrigation), Ms would have no influence due to the absence of Ms variations (Lai et al., 2017). In the other sites, as mentioned above, high Ms has been shown to impede the diffusion of CO_2 in soil (Skoop et al., 1990), and low water content can inhibit soil microbial respiration (Curiel Yuste et al., 2003), as shown through the Gaussian approach. In common with Almagro et al. (2009), a different pattern based on Ts was found: the relationship between Rs and Ms was negative under 16 °C, and positive above this value in both sites. This result could be explained by two factors: first, the low microbial activity at low temperatures, so increased Ms does not lead to any rise in CO_2 emissions; and secondly, a high Ms may be due to the partial dissolution of CO_2 in the water and its transformation into soluble hydrogen carbonate, which is then washed out of the soil profile (Rochette et al., 2004). In this work, the predominant influence of Ts on Rs at medium and high Ts (> 16 °C) could substantially reduce the effect of Ms compared to low Ts, where the correlation was negative. The influence of Ms on Rs is commonly described by simple empirical equations (Jia et al., 2007); however, this shift in the relationship between Ms and Rs demonstrates the inaccuracy of these models, and reinforces the Gaussian approach. Despite the higher water deficit in Madrid and the fallow land use (which could produce a crust, hindering gas exchange between soil and atmosphere), soil water content had a greater effect in Berchidda, except when the soil had very low Ms values, below wilting point.

4.2.3. Synergic effects of Ts and Ms on Rh

The effect of climate factors should not be studied separately when analysing *in situ* data, as their combined impact is more complex than the sum of their individual effects, especially when working in environments with high variability (Almagro et al., 2009). Our modification of the Martin and Bolstad model reflects the crucial impact of Ts on soil CO_2 emissions, which is shown to be the main driver of Rs dynamics. Almost all Rs studies conclude that Rs variability is driven by Ts (Conant et al., 2004; Balogh et al., 2011), and only the most recent studies in dry areas have shown that although Ts is the main factor in Rs variability, the response is modulated by Ms (Almagro et al., 2009; Lellei-Kovács et al., 2011). Although the interaction between these two variables has an effect on Rs, it is far from being the main factor, as shown by the model's application in one Spanish study (González-Ubierna et al., 2014). This effect could be masked by the combination of different studies and land uses.

The relation between Ts and Rs was found to vary at different Ms thresholds in the Mediterranean climate scenario. However, one unexpected result was that Rs in Madrid and Berchidda revealed different behaviour: Ts had the lowest effect when Ms was near the optimum for soil microbial activity, and was even negative in Madrid. These results can be explained as the combined effect of Ms on Rs sensitivity to Ts when Ms is limiting (Davidson et al., 1998). A negative correlation was consistently found in Berchidda when soil water content was below optimum. This effect could be related in this case with intense dry periods, given the high Ts and the low Ms (the most extreme of the three locations) observed in this site. As an effect of the irrigation practices (with high water inputs) in Arborea, no relation was found between Ms and Rs in Ts thresholds. The Arborea site therefore showed the greatest effect of Ts on Rs, particularly in the summer period when soil microbial activity is triggered by organic fertilization in maize. Therefore Arborea site showed a peculiar behaviour, in soil respiration and in the relationships with climatic factors, given by high agronomic input.

Although Ms and Ts were considered two alternative factors affecting the temporal dynamics of Rs (Rey et al., 2002) in a Mediterranean climate, our findings point to Ms and Ts as being complementary rather than alternative factors affecting Rs, concurring with Almagro et al. (2009). The frequency of the measurements (see González-Ubierna et al., 2014; Lai, 2011, Lai et al., 2012 and Lai et al., 2017) due to the use of the portable closed chamber methodology did not allow the exploration of Ts effects at different Ms levels during the dry period. This assessment may require data to be collected on a daily basis in order to uncover the relationship between Ts and Rs in terms of temporal variations on the micro-scale (Qasemian et al., 2014).

5. Conclusions

Mediterranean soil respiration is not yet fully understood, but it is clear today that most of the approaches used to study this complex process in temperate climates cannot be applied in the Mediterranean-type climate because of its high variability. Despite significant differences, and in contrast with other works, soil temperature was the main

driver of soil respiration, in common with temperate sites. However, owing to concurrent changes in climate variables, Ms modulates the response of soil respiration to temperature changes, and is crucial for modelling soil respiration in Mediterranean conditions. The Gaussian approach proved to be the best model for representing these relations, while the use of linear indices is unviable owing to the drastic and simultaneous variation in climate factors.

The results show that irrigation practices with high water inputs substantially modify the pattern of soil respiration, causing it to become similar to temperate soils. The absence of dryness mitigates the impact of the rewetting caused by rainfall, and the consequent priming effect on Rs, and since annual extreme values may be relevant in the relationships between climate variables and soil CO_2 emissions under the Mediterranean-type climate, the lack of the lowest soil water contents in these soils causes them to behave differently. Finally, one of the main characteristics of the Mediterranean-type climate is the simultaneous conjunction of high temperatures and low moisture (summer), unlike other climates; this feature is altered by irrigation, thus blurring a part of their Mediterranean character.

Acknowledgements

We would like to thank Ms Pru Brooke-Turner for her careful revision of the English version of the text. We also thank Dr. Maria del Carmen Bravo for her help with the statistical analyses and their interpretation.

References

Almagro, M., López, J., Querejeta, J.I., Martínez-Mena, M., 2009. Temperature dependence of soil CO_2 efflux is strongly modulated by seasonal patterns of moisture availability in a Mediterranean ecosystem. Soil Biol. Biochem. 41, 594–605.

Álvaro-Fuentes, J., López, M.V., Arrúe, J.L., Moret, D., Paustian, K., 2009. Tillage and cropping effects on soil organic carbon in Mediterranean semiarid agroecosystems: testing the Century model. Agric. Ecosyst. Environ. 134, 211–217.

Bagella, S., Satta, A., Floris, I., Caria, M.C., Rossetti, I., Podani, J., 2013. Effects of plant community composition and flowering phenology on honeybee foraging in Mediterranean sylvo-pastoral systems. Appl. Veg. Sci. 16, 689–697.

Balogh, J., Pintér, K., Fóti, S.Z., Cserhalmi, D., Papp, M., Nagy, Z., 2011. Dependence of soil respiration on soil moisture, clay content, soil organic matter, and CO_2 uptake in dry grasslands. Soil Biol. Biochem. 43, 1006–1013.

Bond-Lamberty, B., Thomson, A., 2010. Temperature-associated increases in the global soil respiration record. Nature 464, 579–582.

Cappai, C., Kemanian, A.R., Lagomarsino, A., Roggero, P.P., Lai, R., Agnelli, E.A., Seddaiu, G., 2017. Small-scale spatial variation of soil organic matter pools generated by cork oak trees in Mediterranean agro-silvo-pastoral systems. Geoderma 304, 59–67.

Cardenas-Lailhacar, B., Dukes, M.D., 2010. Precision of soil moisture sensor irrigation controllers under field conditions. Agric. Water Manag. 97, 666–672.

Carmignani, L., Oggiano, G., Funedda, A., Conti, P., Pasci, S., Barca, S., 2008. Carta Geologica Della Sardegna. Scala 1:250.000. Litografia Artistica Cartografica, Firenze.

Chasermeiro, M.A., Castaño, S., de la Cruz, M.T., García-Montero, L.G., Hernando, M.I., Navarro-García, F., 2007. Metodología para estudiar el impacto sobre el cambio climático de la aplicación de lodos de depuradora al suelo. Efectos en el secuestro de carbono. In: Chasermeiro, M.A., Espluga, A.P., Desdentado, L.D., Díaz, M., García-Montero, L.G., Sobrini, I., Andrés, M. (Eds.), Evaluación de Impacto Ambiental en España: nuevas perspectivas. Asociación Española de EIA, Madrid, pp. 29–34.

Castillo-Monroy, A.P., Maestre, F.T., Rey, A., Soliveres, S., Garcia-Palacios, P., 2011. Biological soil crust microsites are the main contributor to soil respiration in a semiarid ecosystem. Ecosystems 14, 835–847.

Conant, R.T., 2009. Challenges and Opportunities for Carbon Sequestration in Grassland Systems: a Technical Report on Grassland Management and Climate Change Mitigation. Prepared for the. UN Food and Agriculture Organization; Crop and Grassland Service, Plant Production and Protection Division.

Conant, R.T., Klopatek, J.M., Klopatek, C.C., 2000. Environmental factors controlling soil respiration in three semiarid ecosystems. Soil Sci. Soc. Am. J. 64, 383–390.

Conant, R.T., Dalla-Bettab, P., Klopatek, C.C., Klopatek, J.M., 2004. Controls on soil respiration in semiarid soils. Soil Biol. Biochem. 35, 945–951.

Correia, A.C., Minunno, F., Caldeira, M.C., Banza, J., Mateus, J., Carneiro, M., Wingate, L., Shvaleva, A., Ramos, A., Jongen, M., Bugalho, M.N., Nogueira, C., Lecomte, X., Pereira, J.S., 2012. Soil water availability strongly modulates soil CO2 efflux in different Mediterranean ecosystems: model calibration using the Bayesian approach. Agric. Ecosyst. Environ. 161, 88–100.

Craine, J.M., Gelderman, T.M., 2011. Soil moisture controls on temperature sensitivity of soil organic carbon decomposition for a mesic grassland. Soil Biol. Biochem. 43 (2), 455–457.

Curiel Yuste, J., Janssens, I.A., Carrara, A., Meiresonne, L., Ceulemans, R., 2003. Interactive effects of temperature and precipitation on soil respiration in a temperate maritime pine forest. Tree Physiol. 23, 1263–1270.

Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165–173.

Davidson, E.A., Belk, E., Boone, R.D., 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. Glob. Chang. Biol. 4, 217–227.

de Dato, G.D., De Angelis, P., Sirca, C., Beier, C., 2010. Impact of drought and increasing temperatures on soil CO_2 emissions in a Mediterranean shrubland (gariga). Plant Soil 327, 153–166.

Demurtas, C.E., Seddaiu, G., Ledda, L., Cappai, C., Doro, L., Carletti, A., Roggero, P.P., 2016. Replacing organic with mineral N fertilization does not reduce nitrate leaching in double crop forage systems under Mediterranean conditions. Agric. Ecosyst. Environ. 219, 83–92.

Fang, C., Moncrieff, J.B., 2001. The dependence of soil CO_2 efflux on temperature. Soil Biol. Biochem. 33, 155–165.

Francaviglia, R., Coleman, K., Whitmore, A.P., Doro, L., Urracci, G., Rubino, M., Ledda, L., 2012. Changes in soil organic carbon and climate change – application of the RothC model in agrosilvo-pastoral Mediterranean systems. Agrultural Systems 112, 48–54.

Gaumont-Guay, D., Black, T.A., Griffis, T.J., Barr, A.G., Jassal, R.S., Nesic, Z., 2006. Interpreting the dependence of soil respiration on soil temperature and water content in a boreal aspen stand. Agric. Forest Meteorol. 140, 220–235.

Gershenson, A., Bader, N.E., Cheng, W.X., 2009. Effects of substrate availability on the temperature sensitivity of soil organic matter decomposition. Glob. Chang. Biol. 15, 176–183.

González-Ubierna, S., Jorge-Mardomingo, I., Carrero-González, B., de la Cruz, M.T., Chasermeiro, M.A., 2012. Soil organic matter evolution after the application of high rates of organic amendments in a Mediterranean calcareous soil. J. Soils Sediments 12, 1257–1268.

González-Ubierna, S., Jorge-Mardomingo, I., de la Cruz, M.T., Valverde, I., Chasermeiro, M.A., 2013. Sewage sludge application on Mediterranean soil: dose effects upon soil carbon cycle. Int. J. Environ. Res. 7, 945–956.

González-Ubierna, S., de la Cruz, M.T., Chasermeiro, M.A., 2014. Climate factors mediate soil respiration dynamics in Mediterranean agricultural environments: an empirical approach. Soil Res. 52, 543–553.

González-Ubierna, S., de la Cruz, M.T., Chasermeiro, M.A., 2015. How do biodegradable organic residues affect soil CO_2 emissions? Case study of a Mediterranean agro-ecosystem. Soil and Tillaje Research 153, 48–58.

Hamer, U., Marschner, B., 2005. Priming effects in different soil types induced by fructose, alanine, oxalic acid and catechol additions. Soil Biol. Biochem. 37, 445–454.

Hanson, P.J., Edwards, N.T., Garten, C.T., Andrews, J.A., 2000. Separating root and soil microbial contribution to soil respiration: a review of methods and observations. Biogeochemistry 48, 115–146.

Inglima, I., Alberti, G., Bertolini, T., Vaccari, F.P., Gioli, B., Miglietta, F., Cotrufo, M.F., Peressotti, A., 2009. Precipitation pulses enhance respiration of Mediterranean ecosystems: the balance between organic and inorganic components of increased soil CO_2 efflux. Glob. Chang. Biol. 15, 1289–1301.

Jarvis, P., Rey, A., Petsikos, C., Wingate, L., Rayment, M., Pereira, J., Banza, J., David, J., Miglietta, F., Borghetti, M., Manca, G., Valentini, R., 2007. Drying and wetting of Mediterranean soils stimulates decomposition and carbon dioxide emission: the Birch effect. Tree Physiol. 27, 929–940.

Jia, B., Zhou, G., Yuan, W., 2007. Modelling and coupling of soil respiration and soil water content in fenced Leymus chinensis steppe, Inner Mongolia. Ecol. Model. 201, 157–162.

Jiménez-Hernández, M.E., de la Losa-Román, A., Valverde-Asenjo, M.I., Moreno-Merino, L., Castaño-Castaño, S., 2009. In: In: Silva, O. (Ed.), Caracterización de las propiedades hidráulicas de la zns: determinaciones en laboratorio y ensayos “in situ” en una parcela agrícola de Arganda del Rey (Madrid), vol. IX Estudios en la Zona no Saturada del Suelo, Barcelona 18 a 20 de Noviembre, 2009.

Joffre, R., Ourcival, J.M., Rambal, S., Rocheteau, A., 2003. The key-role of topsoil moisture on CO2 efflux from a Mediterranean Quercus ilex forest. Ann. For. Sci. 60, 519–526.

Kuzyakov, Y., Friedel, J.K., Stahr, K., 2000. Review of mechanisms and quantification of priming effects. Soil Biol. Biochem. 32, 1485–1498.

Lagomarsino, A., Benedetti, A., Marinari, S., Pompili, L., Moscatelli, M.C., Roggero, P.P., Lai, R., Ledda, L., Grego, S., 2011. Soil organic C variability and microbial functions in a Mediterranean agro-forest ecosystem. Biol. Fertil. Soils 47, 283–291.

Lai, R., 2011. Dinamica Spazio-temporale della Respirazione Eterotrofa del Suolo in un Sistema Agrario Mediterraneo. PhD Thesis. Scuola di dottorato di ricerca Scienze dei Sistemi Agrari e Forestali e delle Produzioni Alimentari. Università degli Studi di Sassari.

Lai, R., Seddaiu, G., Gennaro, L., Roggero, P.P., 2012. Effects of nitrogen fertilizer sources and temperature on soil CO_2 efflux in Italian ryegrass crop under Mediterranean conditions. Ital. J. Agron. 7, 196–201.

Lai, R., Lagomarsino, A., Ledda, L., Roggero, P.P., 2014. Variation in soil C and microbial functions across tree canopy projection and open grassland microenvironments. Turk. J. Agric. For. 38, 62–69.

Lai, R., Arca, P., Lagomarsino, A., Cappai, C., Seddaiu, G., Demurtas, C.E., Roggero, P.P., 2017. Manure fertilization increases soil respiration and creates a negative carbon budget in a Mediterranean maize (Zea mays L.)-based cropping system. Catena 151, 202–212.

Leifeld, J., Zimmermann, M., Fuhrer, J., 2008. Simulating decomposition of labile soil organic carbon: effects of pH. Soil Biol. Biochem. 40, 2948–2951.

Lellei-Kovács, E., Kovács-Láng, E., Botta-Dukát, Z., Kalapos, T., Emmet, B., Beier, C., 2011. Thresholds and interactive effects of soil moisture on the temperature response of soil respiration. Eur. J. Soil Biol. 47, 247–255.

Li, H., Yan, J., Yue, X., Wang, M., 2008. Significance of soil temperature and moisture for soil respiration in a Chinese mountain area. Agric. For. Meteorol. 148, 490–503.
Lloyd, J., Taylor, J.A., 1994. On the temperature dependence of soil respiration. Funct. Ecol. 8, 315–323.
López-López, G., Lobod, M.C., Negre, A., Colombàs, M., Rovira, J.M., Martorell, A., Reolid, C., Sastre-Conde, I., 2006. Impact of fertilisation practices on soil respiration, as measured by the metabolic index of short-term nitrogen input behaviour. J. Environ. Manag. 113, 517–526.
Luo, Y., Zhou, X., 2006. Soil Respiration and the Environment. Elsevier/Academic Press, Amsterdam 316 pp.
Mancinelli, R., Campiglia, E., Di Tizio, A., Marinari, S., 2010. Soil carbon dioxide emission and carbon content as affected by conventional and organic cropping systems in Mediterranean environment. Appl. Soil Ecol. 46, 64–72.
Martin, J.G., Bolstad, P.V., 2009. Variation of soil respiration at three spatial scales: components within measurements, intra-site variation and patterns on the landscape. Soil Biol. Biochem. 41, 530–543.
Matteucci, M., Gruening, C., Goded Ballarin, I., Seufert, G., Cescatti, A., 2015. Components, drivers and temporal dynamics of ecosystem respiration in a Mediterranean pine forest. Soil Biol. Biochem. 88, 224–235.
Migliavacca, M., Reichstein, M., Richardson, A.D., Colombo, R., Sutton, M.A., Lasslop, G., Tomelleri, E., Wohlfahrt, G., Carvalhais, N., Cescatti, A., Mahecha, M.D., Montagnani, L., Papale, D., Zaehle, S., Arain, A., Arneth, V., Black, T.A., Carrara, A., Dore, S., Gianelle, D., Helfter, C., Hollinger, D., Kutsch, W.L., Lafleur, P.M., Nouvellon, Y., Rebmann, C., da Rocha, H.R., Rodeghiero, M., Roupsard, O., Sebastia, M.T., Seufert, G., Soussana, J.F., van der Molen, M.K., 2011. Semiempirical modeling of abiotic and biotic factors controlling ecosystem respiration across eddy covariance sites. Glob. Chang. Biol. 17, 390–409.
Moyano, F.E., Vasilyeva, N., Bouckaert, L., Cook, F., Craine, J., Curiel Yuste, J., Don, A., Epron, D., Formanek, P., Franzluebbers, A., Ilstedt, U., Katterer, T., Orchard, V., Reichstein, M., Rey, A., Ruamps, L., Subke, J.-A., Thomsen, I.K., Chenu, C., 2012. The moisture response of soil heterotrophic respiration: interaction with soil properties. Biogeosciences 9, 1173–1182.
Navarro-García, F., Chasermeiro, M.A., Schimel, J.P., 2012. When structure means conservation: effect of aggregate structure in controlling microbial responses to rewetting events. Soil Biol. Biochem. 44, 1–6.
Oertel, C., Jörg Matschullat, J., Zurbaa, K., Zimmermanna, F., Erasmi, S., 2016. Greenhouse gas emissions from soils—a review. Chem. Erde 76, 327–352.
Onoyarte, C., Rey, A., Raimundo, J., Miralles, I., Escribano, P., 2012. The use of soil respiration as an ecological indicator in arid ecosystems of SE of Spain: spatial variability and controlling factors. Ecol. Indicat. 14, 40–49.
Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532 (7597), 49–57.
Portner, H., Bugmann, H., Wolf, A., 2010. Temperature response functions introduce high uncertainty in modelled carbon stocks in cold temperature regimes. Biogeosciences 7, 3669–3684.
Pulina, A., Lai, R., Salis, L., Seddaiu, G., Roggero, P.P., Bellocchi, G., 2017. Modelling pasture production and soil temperature, water and carbon fluxes in Mediterranean grassland systems with the Pasture Simulation Model. Grass Forage Sci. 73, 272–283.
Qasemian, L., Guiral, D., Farnet, A.M., 2014. How do microlocal environmental variations affect microbial activities of a Pinus halepensis litter in a Mediterranean coastal area? Sci. Total Environ. 496, 198–205.
Rambal, S., 2001. Spatial and temporal variations in productivity of Mediterranean-type ecosystems: a hierarchical perspective. In: Mooney, H.A., Saugier, B., Roy, J. (Eds.), Terrestrial Global Productivity: Past Present, Future. Academic, San Diego, California, pp. 45–61 2001.
Rey, A., Pegoraro, E., Tedeschi, V., De Parri, I., Jarvis, P.G., Valentini, R., 2002. Annual variation in soil respiration and its components in a coppice oak forest in Central Italy. Glob. Chang. Biol. 8, 851–866.
Rivas-Martínez, S., Rivas-Sáenz, S., Penas, A., 2011. Worldwide bioclimatic classification system. Global Geobotany 1, 1–634.
Rochette, P., Angers, D.A., Chantigny, M.H., Bertrand, N., Côté, D., 2004. Carbon dioxide and nitrous oxide emissions following fall and spring applications of pig slurry to an agricultural soil. Soil Sci. Soc. Am. J. 68, 1410–1420.
Savage, K., Davidson, E., 2003. A comparison of manual and automated systems for soil CO2 flux measurements: trade-offs between spatial and temporal resolution. J. Exp. Bot. 54, 891–899.
Scholes, R.J., Monteiro, P.M.S., Sabine, C.L., Canadell, J.G., 2009. Systematic long-term observations of the global carbon cycle. Trends Ecol. Evol. 24, 427–430.
Scott-Denton, L.E., Rosenstiel, T.N., Monson, R.K., 2005. Differential controls by climate and substrate over the heterotrophic and rhizospheric components of soil respiration. Glob. Chang. Biol. 11, 1–12.
Seddaiu, G., Porcu, G., Ledda, L., Roggero, P.P., Agnelli, A., Corti, G., 2013. Soil organic matter content and composition as influenced by soil management in a semi-arid Mediterranean agro-silvo-pastoral system. Agric. Ecosyst. Environ. 167, 1–11.
Skopp, J., Jawson, M.D., Doran, J.W., 1990. Steady-state aerobic microbial activity as a function of soil water content. Soil Sci. Soc. Am. J. 54, 1619–1625.
Subke, J.A., Bahn, M., 2010. On the 'temperature sensitivity' of soil respiration: can we use the immeasurable to predict the unknown? Soil Biol. Biochem. 42, 1653–1656.
Suseela, V., Tharayil, N., Xing, B., Dukes, J.S., 2014. Warming alters potential enzyme activity but precipitation regulates chemical transformations in grass litter exposed to simulated climatic changes. Soil Biol. Biochem. 75, 102–112.
Thierron, V., Laudelout, H., 1996. Contribution of root respiration to total CO2 efflux from the soil of a deciduous forest. Can. J. For. Res. 26, 1142–1148.
Trumbore, S., 2006. Carbon respired by terrestrial ecosystems e recent advances and challenges. Glob. Chang. Biol. 12, 141–153.
Tuomi, M., Vanhala, P., Karhu, K., Fritze, H., Liski, J., 2008. Heterotrophic soil respiration – comparison of different models describing its temperature dependence. Ecol. Model. 211, 182–190.
Unger, S., Maguas, C., Pereira, J.S., David, T.S., Werner, C., 2012. Interpreting post-drought rewetting effects on soil and ecosystem carbon dynamics in a Mediterranean oak savannah. Agric. For. Meteorol. 154, 9e18.
Vargas, R., Allen, M.F., 2008. Environmental controls and the influence of vegetation type, fine roots and rhizomorphs on diel and seasonal variation in soil respiration. New Phytol. 179, 460–471.
Verburg, P.S.J., Arnone, J.A., Obrist, D., Schorran, D.E., Evans, R.D., Leroux-swarthout, D., Johnson, D.W., Luo, Y., Coleman, J.S., 2004. Net ecosystem exchange in two experimental grassland ecosystems. Glob. Chang. Biol. 10, 498–508.
von Lützow, M., Kögel-Knabner, I., 2009. Temperature sensitivity of soil organic matter decomposition—what do we know? Biol. Fertil. Soils 46, 1–15.
Walse, C., Berg, B., Svedrup, H., 1998. Review and Synthesis of Experimental Data on Organic Matter Decomposition with Respect to the Effects of Temperature, Moisture, and Acidity, vol. 6. Environmental Reviews, pp. 25–40.
Webster, K.L., Creed, I.F., Showronski, M.D., Kaheil, Y.H., 2009. Comparison of the performance of statistical model that predict soil respiration from forests. Soil Sci. Soc. Am. J. 73, 1157–1167.
WRB, 2006. World Reference Base for Soil Resources World Soil Resources Report 103. IUSS, ISRIC, FAO, Rome.
Xiao, S., Ye, G., Zhang, L., Jin, Z., Liu, L., 2009. Soil heterotrophic respiration in *Casuarina equisetifolia* plantation at different stand ages. J. For. Res. 20 (4), 301–306.
Xu, M., Qi, Y., 2001. Spatial and seasonal variations of Q10 determined by soil respiration measurements at Sierra Nevadan forest. Glob. Biogeochem. Cycles 15, 687–696.
Zhang, L.H., Chen, Y.N., Zhao, R.F., Li, W.H., 2010. Significance of temperature and soil water content on soil respiration in three desert ecosystems in Northwest China. J. Arid Environ. 74, 1200–1211.
Zhang, X.B., Xu, M.G., Sun, N., Wang, X.J., Wu, L., Wang, B.R., Li, D.C., 2013. How do environmental factors and different fertilizer strategies affect soil CO_2 emission and carbon sequestration in the upland soils of southern China? Appl. Soil Ecol. 72, 109–118.